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LOCOMOTIVE ENERGY SAVINGS POSSIBILITIES

Summary. Economic indicators of electrodynamic braking have not been properly estimated. Vehicles with alternative power trains are transitional stage between development of pollution- free vehicles. According to these aspects the investigation on conventional hybrids drives and their control system is carried out in the article. The equation that allows evaluating effectiveness of regenerative braking for different variants of hybrid drive are given. Presenting different types of locomotive energy savings power systems, which are using regenerative braking energy any form of hybrid traction vehicles systems, circuit diagrams, electrical parameters curves.

ВОЗМОЖНОСТИ ЭКОНОМИИ ЭНЕРГИИ ЛОКОМОТИВОВ

Аннотация. В статье рассматриваются новые возможности экономии энергии локомотивов. Отображены возможности рекуперации энергии электроподвижного состава в контактную сеть на высоких скоростях движения и накопления энергии на низких скоростях движения. Предложены варианты структуры гибридных локомотивов с использованием тендера для накопительных батарей. Представлены схемы, диаграммы, графики, отображающие возможности использования рекуперативного торможения.

1. INTRODUCTION

Different evaluations vehicles type 20-40% of mechanical tractive power is lost during braking. Estimation of recovered energy is very important. When a vehicle brakes, energy is released to date, most of this energy has been lost in air. The challenging alternative is to store the braking energy on the train, use it during acceleration of operation of the vehicle. Conventional diesel locomotives powered electrical transmission cannot use regenerative brake energy. Estimation of recovered energy is very important. It is needed to reduce electric demand, it is used new energy savings and power supply optimization, hybrid traction vehicles systems, which are using regenerative braking energy.

2. NEW LOCOMOTIVE ELECTRODYNAMIC BRAKING SYSTEMS

Locomotive electric braking system may be divided into dynamic, and regenerative. The energy generated in the dynamic braking mode is typically transferred to resistance girds mounted on the locomotive housing. Thus, the dynamic braking energy is converted to heat and dissipated from the system. In other words, electric energy generated is typically wasted. In a typical prior art DC locomotive, the dynamic braking grids (braking resistor R_b module) are connected to the traction motors. Regenerative braking is more energy-effective because power given to catenary power system is either used by another electric train or returned to the power system. More than 25% of power used for traction can be returned to catenary power system.

Thus, the conditions for the traction motor at idle to exceed point n_0 of torque-speed characteristic $n = f(M)$, which is required in regenerative braking, cannot be satisfied (see Fig. 1).

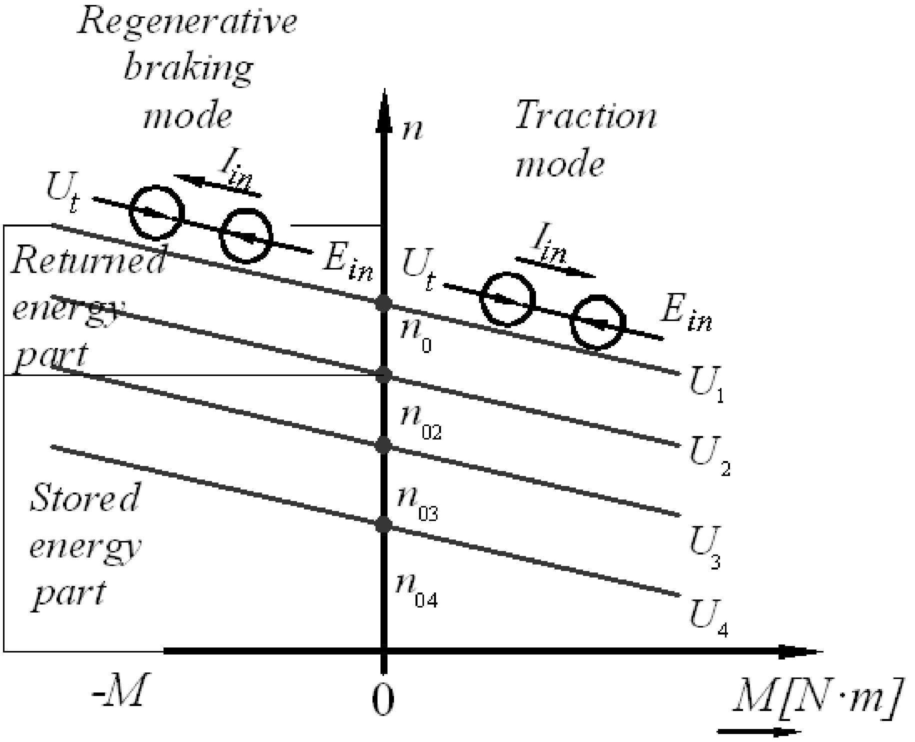

Fig. 1. Torque-speed characteristic of shunt-wound excitation DC traction motor's regenerative braking and traction modes: *I* – returned energy part; *II* – stored energy part; n_0 is traction motor's no-load speed; U_t is catenary system voltage; I_{in} is armature current of DC traction motor

Рис. 1. Механические характеристики DC независимого возбуждения тягового двигателя в режимах тяги и рекуперативного торможения: *I* – часть возвращаемой энергии в сеть; *II* – часть накапливаемой энергии; n_0 – идеальная скорость холостого хода; U_t – напряжение контрольной сети; I_{in} – ток якоря DC тягового двигателя

When the load moment changes (e.g. when the locomotive is moving down the slope), the speed n of the motor armature exceeds n_0, e.m.f. of the motor E exceeds network voltage, the armature current is reversed and electromagnetic braking moment is developed (see Fig 1). The traction motor goes to the generator mode, while electromagnetic moment, which is a counter torque with respect to the armature, becomes a braking moment, and the power produced by the generator is given to the catenary (energy power supply system). Figure 1 shows principle of the braking energy management system new possibilities, when part of regenerative braking energy returned in to energy supply system and part of energy stored storage battery. The power of modern electric trains, like TGV in France, ICE in Germany, high speed electric trains in Japan, reach to 10 MW, therefore, brake power is very high. It can be found from the power balance equation as follows:

$$P_m = P_e + \Delta P, \tag{1}$$

where is P_m – the mechanical power of the motor shaft, W; P_e is the electric power given to electricity supply network, W; ΔP – denotes total power losses of the electric circuit of the motor, W.

3. AC TRACTION MOTORS SPEED CONTROL METHODS

The speed of the tree-phase induction motor is determined by the numbers pairs of poles p of the motor, the mains frequency f_1 and the motors sleep s. The different possibilities to control the speed of a three-phase induction motor arises from this dependence. From the equation

$$n_0 = \frac{60 \cdot f_1}{p}. \tag{2}$$

3.1. Speed control by pole changing

Numbers pole pairs changing doesn't allow full control of the speed. It only allows to select between less fixed speeds e.g. by changing the stator winding from one pair of poles $p = 1$ to $p = 2$. This gives, with a mains frequency of 50 Hz and the usual numbers of pairs, the synchronous speeds is, then $p = 1$, $n_0 = 3\ 000$ rpm, then $p = 2$, $n_0 = 1\ 500$ rpm.

3.2. Speed control by changing the frequency

The most modern kind of speed control of three-phase induction motors is the control by changing frequency f_1. It ensures a wide control of range of the speed and causes only little additional losses. The frequency controlled squirrel-cage induction motor can be easily showed down by reducing the supply frequency. If, by that, the motor is driven by the load, it changes to the generator operation and begins to feed back energy. This energy must be either fed back into three-phase supply network or transformed into head trough a braking resistor.

Regenerative braking should be used by AC traction motors. When the AC traction motor load moment changes the speed n of the AC traction motor rotor speed exceeds n_0 the traction motor goes to the generator mode, while electromagnetic braking moment is developed. Traction motor's no-load speed n_0 is possible by changing the frequency f_1 and to receive more regenerative braking characteristics and regenerative braking energy returned to network supply or charging storage battery. Figuer 2 shows AC traction motors speed control by changing mains frequency f_1 operate traction and regenerative braking mode.

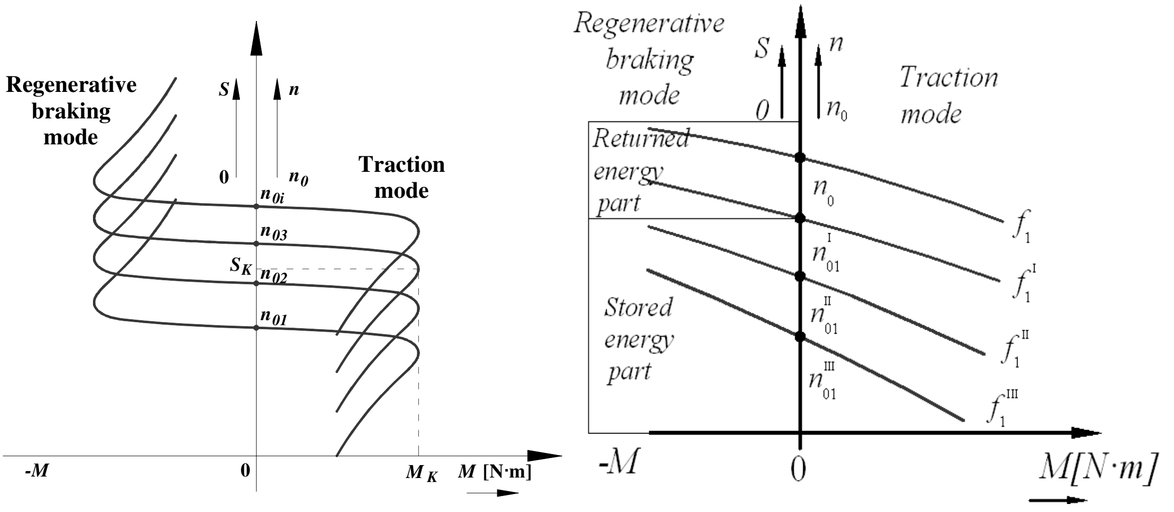

Fig. 2. Torque-speed characteristic of induction traction motor's regenerative braking and traction modes by changing mains frequency f_1: $n_{01} - n_{0i}$ is AC traction motor's no-load speed; S_k – slip at pull-out torque; M_k – pull-out torque

Рис. 2. Механические характеристики АС тягового двигателя в режимах тяги и рекуперативного торможения при изменении частоты питания f_1: $n_{01} - n_{0i}$ – идеальные скорости холостого хода АС тягового двигателя; S_k – критическое скольжение; M_k – критический момент

By changing simultaneously the supply voltage U_1 and its frequency f_1, depending on mode regulation, any flat characteristics can be obtained. Figure 2 shows principle of the braking energy management system used AC/AC electric locomotive, when part of regenerative braking energy returned in to energy supply system and part of energy stored storage battery.

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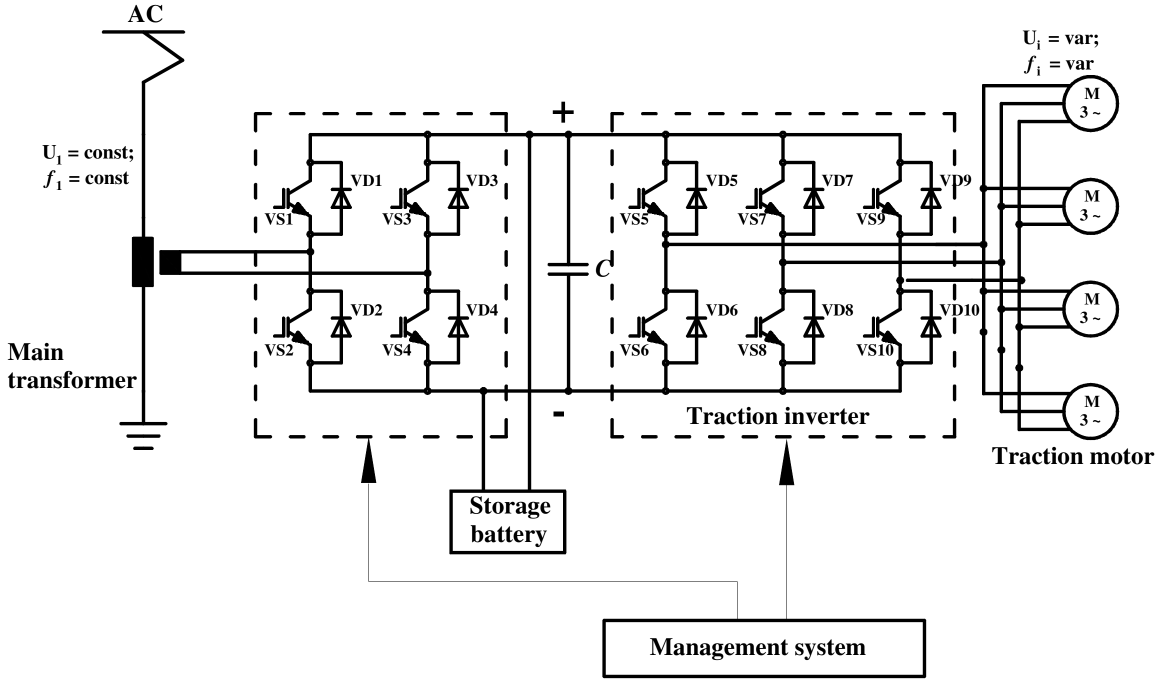

Fig. 3. A circuit diagram of AC/AC electric locomotive regenerative braking energy management system
Рис. 3. Электрическая схема управление энергией рекуперативного торможения AC/AC системы электрического локомотива

Authors suggested in conventional electric locomotive to install storage battery. Figure 3 shows principle of the braking energy management system used AC/AC electric locomotive, when part of regenerative braking energy returned in to energy supply system and part of energy stored storage battery.

4. HYBRID TRACTION PROPULSION SYSTEM

Hybrid traction energy saving propulsion system using storage-battery technology. As the train using its traction motors the authors suggest to use a hybrid propulsion system combining an engine generator with storage batteries. A hybrid energy locomotive system having an energy storage and regeneration system. The traction batteries store the regenerated electrical power that would have otherwise been wasted in heat using friction/dynamic braking. Using regenerative braking, fuel consumption is minimized. Peak levels of energy efficiency are regulated by the energy management system. The energy storage and regeneration system captures dynamic braking energy, excess motor energy, and externally supplied energy, and stores the energy in one or more energy storage subsystem, including a flywheel, a battery, an ultra – capacitor, or combination of such subsystems. The energy storage and regeneration system can be located in a separate energy tender vehicle. The energy management system controls the storage and regeneration of energy accordingly. Any recovered energy can be used for traction. This system provides regenerative braking not previously possible on conventional diesel-powered trains, and this makes it possible to increase energy savings via regenerated energy. In one form, the system can be retrofitted into existing locomotives or installed as original equipment. Conventional diesel locomotives powered electrical transmission can not use regenerative braking energy. As the train using its traction motors, the storage batteries store the regenerated electrical power that would have otherwise been wasted in heat using friction/dynamic braking. Using regenerative braking, fuel consumption is minimized. Peak levels of energy efficiency are regulated by the energy management system. Any recovered energy can be used for traction.

This is expected to give fuel savings of approximately 20-25% compared with conventional diesel-powered trains. This system uses a series-hybrid configuration (see Fig. 4) that first converts the engine output into electrical power and then uses only motors for propulsion. Diesel engine energy is converted by the synchronous traction alternator (generator – GS). The AC (alternating current) output generated by the engine is converted into a VVVF (variable voltage variable frequency converter). Storage batteries are located on the intermediate DC section of the main converter. The charging and discharging of the storage batteries are controlled using output adjustments of the converter and inverter. Storage batteries charging and discharging processes are controlled by the converter and inverter output for management system. Under braking, the engine is stopped**.** The traction motors act as generators, and recovered energy is used to charge the batteries. Storage battery operation of charging mode.

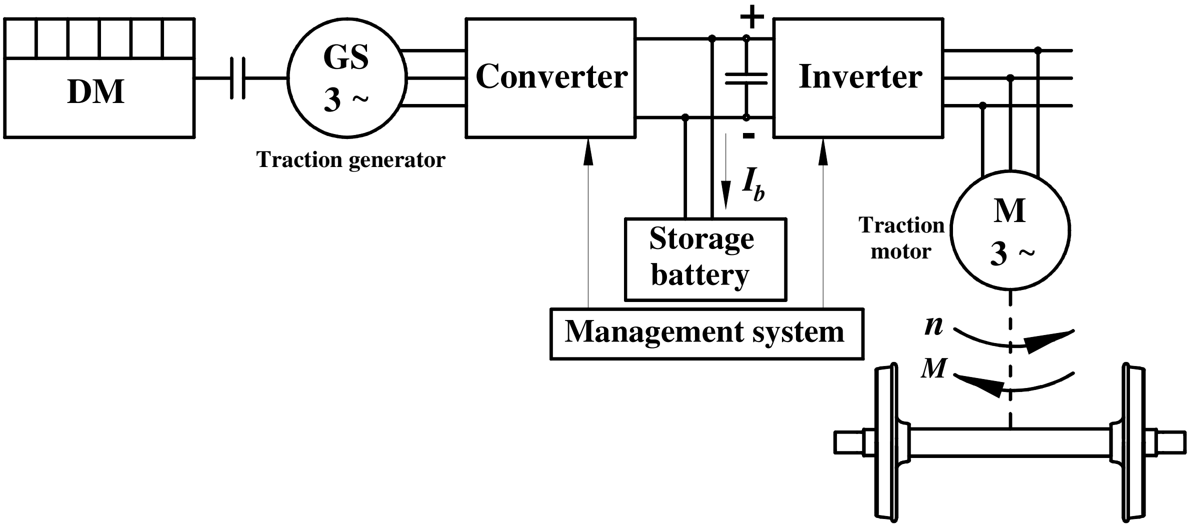

Fig. 4. A circuit diagram of Hybrid Traction System (regenerative braking mode): DM – diesel engine; G – synchronous traction alternator (generator); I_b – regenerative braking current; SB – storage battery; M – induction traction motor

Рис. 4. Схема тяговой гибридной системы (в режиме рекуперативного торможения): DM – дизельный двигатель; G – синхронный тяговой генератор; I_b – ток рекуперативного торможения; SB – накопительная батарея; M – асинхронный тяговой двигатель

Upon departure, the train accelerates using recovered energy only. Storage battery is in discharging mode. Authors suggested storage battery to install in to energy tender.

Timing diagram shows new locomotive energy management possibilities, traction and regenerative braking mode. Timing diagram illustrating the hybrid traction system energy storage possibilities: $0 - t_1$, $t_2 - t_3$ – time cycles of using powered storage energy traction and auxiliary equipment mode; $t_1 - t_2$ time cycles of stored energy mode.

5. ENERGY BALANCE

Within the bounds of the present research the question of qualitative evaluation of regenerative power during hybrid vehicle braking is of fundamental importance.

Vehicle power during braking on horizontal road P_{br} can be expressed by the following equation:

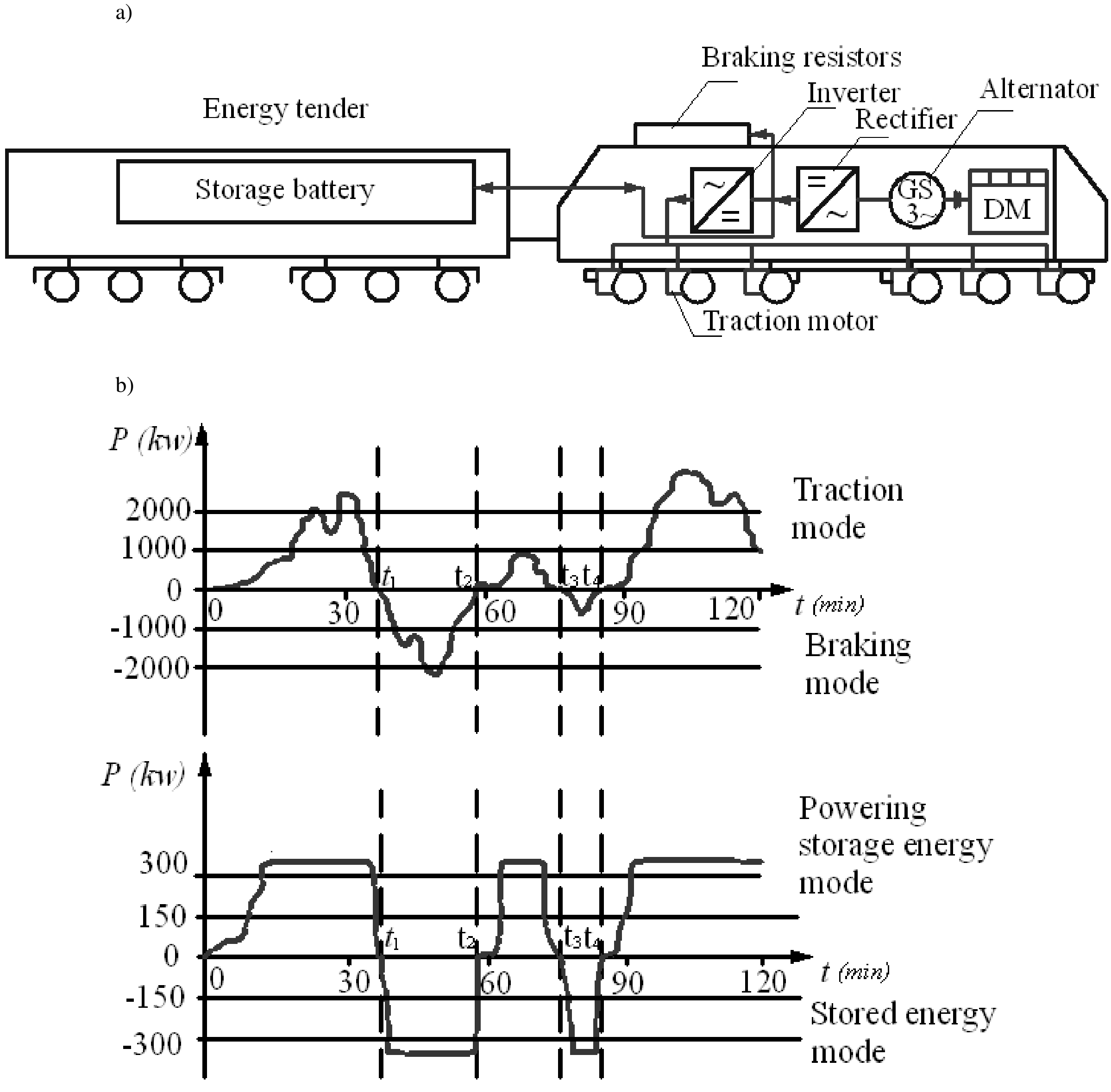

Fig. 5. Circuit (a) and timing diagram (b) of hybrid energy traction system using energy tender vehicle
Рис. 5. Схема и временные диаграммы тяговой гибридной системы с использованием тендера накопительных батарей

$$P_{br} = k_m \cdot m \cdot a \cdot V\,, \tag{3}$$

where: k_m – coefficient of rotational masses; m – vehicle mass; a – vehicle acceleration (deceleration); V – vehicle velocity.

The power, that can be received during regenerative braking is:

$$P_{regen} = k_m \cdot m \cdot a \cdot V \cdot \eta_{regen}\,, \tag{4}$$

where: k_m – coefficient of rotational masses; m – vehicle mass; a – vehicle acceleration (deceleration); V – vehicle velocity; η_{regen} – efficiency of regenerative braking (can be defined as rate of energy, received during braking up to decrease of vehicle kinetic energy).

At the same time, regenerative braking power can be considered as electric power, that finally receives the storage element (in this case storage battery):

$$P_{regen} = P_{el} = I_{bat} \cdot U_{bat}\,, \tag{5}$$

where: P_{el} – electric power that receives battery; I_{bat} – battery current; U_{bat} – battery voltage.

The effectiveness of regenerative braking can be estimated using these equations:

$$\eta_{regen} = \frac{P_{regen}}{P_{br}} = \frac{I_{bat} \cdot U_{bat}}{k_m \cdot m \cdot a \cdot V}\,. \tag{6}$$

6. CONCLUSIONS

1. Electrics locomotives use regenerative braking 25–40% of electric power to be returned to the power system.
2. The required regenerative braking forces can be obtained in a wide range, with possibilities returned energy to energy supply in a high-speed range and stored energy – in a low-speed range.
3. All diesel electric powered locomotives must use hybrid traction technology.
4. Hybrid traction technology locomotives can use regenerative braking of high-speed and a low-speed range.
5. Hybrid traction technology locomotives are reducing 25–30% energy.
6. Asynchronous traction motor to be extensively used in traction, recuperation and dynamic braking modes of operation.
7. A circuit scheme of using hybrid traction technology with energy storage tender is offering.
8. The regenerative braking power can be possibly use in diesel electric locomotives for starting engine, acceleration, and operation mode.

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